Optimization of a DPP-BOTDA sensor with 25 cm spatial resolution over 60 km standard single-mode fiber using Simplex codes and optical pre-amplification

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Abstract: Sub-meter distributed optical fiber sensing based on Brillouin optical time-domain analysis with differential pulse-width pairs (DPP-BOTDA) is combined with the use of optical pre-amplification and pulse coding. In order to provide significant measurement SNR enhancement and to avoid distortions in the Brillouin gain spectrum due to acoustic-wave pre-excitation, the pulse width and duty cycle of Simplex coding based on return-to-zero pulses are optimized through simulations. In addition, the use of linear optical pre-amplification increases the receiver sensitivity and the overall dynamic range of DPP-BOTDA measurements. Experimental results demonstrate for first time a spatial resolution of ~25 cm over a 60 km standard single-mode fiber (equivalent to ~240k discrete sensing points) with temperature resolution of 1.2°C and strain resolution of 24 με.

OCIS codes: (060.2370) Fiber optics sensors; (290.5900) Scattering, stimulated Brillouin; (060.4370) Nonlinear optics, fibers.

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1. Introduction

Distributed optical fiber sensors for temperature and strain measurements are commonly based on Brillouin optical time-domain analysis (BOTDA), exploiting stimulated Brillouin scattering (SBS). This technique allows for a sensing distance of several tens of km with a spatial resolution down to about 1 meter [1, 2], which is limited by the acoustic phonon

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lifetime (of the order of 10 ns). In order to achieve a shorter (i.e. sub-meter) spatial resolution, the use of more complex interrogation schemes is required [3, 4]. Note that distributed sensing with a sub-meter spatial resolution is very important for many applications, such as for structural health monitoring (SHM), where centimeter-scale detection of cracks (within e.g. concrete) in civil engineering structures can lead to early diagnosis of structural damage and prevention of catastrophic events.

Among the several techniques to reach sub-meter resolution, differential pulse-width pair BOTDA (DPP-BOTDA) constitutes an effective scheme to perform distributed sensing with resolution down to centimeter-scale [3]. Such a technique requires the subtraction of two Brillouin signals originating from a light pulse pair with slightly different pulse widths. The subtraction process unfortunately increases the measurement error, decreasing the attained signal-to-noise ratio (SNR) values, and thus strongly reducing the final strain-temperature resolution, especially over long distances. Within DPP-BOTDA, linear coding (e.g. Simplex coding [5]) can then offer a significant improvement due to the SNR enhancement provided by the coding gain [6], which can be exploited to extend the sensing range and enhance the temperature and strain resolutions. Actually, the trade-off between sensing distance and spatial resolution is still an open issue which can be addressed by further optimization of the pulse coding technique and the implementation of optical pre-amplification at the receiver [7].

In this paper, we report on the implementation of a long-range DPP-BOTDA sensor based on Simplex coding [5]. The use of 511-bit Simplex coding, combined with return-to-zero (RZ) modulation format with an optimized duty cycle and linear optical pre-amplification at the receiver, provides significant SNR enhancement and improved sensing performance, attaining a spatial resolution of 25 cm over 60 km standard single-mode fiber (SMF), with a resolution in Brillouin frequency shift (BFS) measurements of ~1.2 MHz, corresponding to ~1.2°C / ~24 με temperature/strain resolution respectively.

2. Theory

In conventional BOTDA sensors, a continuous-wave (CW) probe signal and a counter-propagating optical pump pulse interact with an acoustic wave through stimulated Brillouin scattering (SBS). As a consequence, the CW light is amplified by the pump power while it propagates along the fiber, so that the probe intensity contrast (ΔI_{CW}) at the receiver can be expressed as [2]:

$$\Delta I_{CW}\left(t,\nu\right) \propto \int_{\upsilon_g t/2}^{\upsilon_g t/2+\Delta z} g_B\left(\xi,\nu\right) Ip\left(\xi,\nu\right) d\xi, \quad (1)$$

where v_g is the group velocity, Δz is the interaction length (i.e. the spatial resolution) related to the pump pulse duration, $g_B(\xi,\Delta\nu)$ and $I_P(\xi,\Delta\nu)$ are the Brillouin gain spectrum (BGS) and the pump intensity at position $z = \xi$. From Eq. (1), we see that when a high spatial resolution is required (i.e. for short Δz values), the intensity variations of the CW probe wave (ΔI_{CW}) are reduced, limiting the SNR of the measurements [2, 3]. In addition, when using pump pulse widths shorter than the acoustic-phonon lifetime (~10 ns), the BGS is broadened and consequently the peak Brillouin gain is reduced [8]. These effects lead to inaccuracies in BFS measurements, limiting the achievable spatial resolution of standard BOTDA sensors to ~1 m [1]. In order to achieve distributed sensing with sub-meter spatial resolution over long sensing distances, more sophisticated techniques should be used.

Among sub-meter sensing techniques, DPP-BOTDA [3] has been demonstrated to be effective to perform long-range distributed sensing with cm-scale spatial resolution [3, 4]. In such a scheme, the BGS is obtained by subtracting pairs of BOTDA traces (at each frequency component) resulting from two slightly different input pulse widths. Both pulse widths are actually required to be longer than the phonon lifetime (~10 ns) to avoid detrimental BGS broadening effects [3, 8]. The spatial resolution is, in its turn, determined by the difference between the pulse widths; however, the resolution is finally affected also by other system parameters such as the pulse fall time and the receiver bandwidth. Note that an improved spatial resolution inevitably leads to lower SNR values of the measured BGS, limiting the

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maximum sensing distance to shorter values with respect to standard BOTDA sensors. Moreover, in order to avoid pump depletion when interrogating long sensing fibers [9], a rather low probe signal power must be used, thus reducing both Brillouin gain (i.e. the CW-intensity contrast) and the SNR of BGS measurements [7].

It has been recently demonstrated that optical pulse coding techniques can effectively improve the SNR of conventional BOTDA [2, 7] as well as of DPP-BOTDA sensors. In particular, a spatial resolution of 50 cm has been reported over a 50 km large effective area fiber (LEAF) using a DPP-BOTDA sensor based on Golay codes [6]. To further enhance the spatial resolution over longer distances, a broader receiver bandwidth and a short pulse width difference are required; unfortunately, both requirements lead to a significant SNR reduction, and therefore, a proper optimization of the coding technique and sensor system parameters is needed. Considering that Simplex codes are characterized by several codewords containing the same amount of light pulses, i.e. the same number of '1' bits in each codeword (equal to $(L + 1)/2$ for a code length L) [5], then the effective length and maximum peak power allowed before the onset of nonlinearities are the same for all codewords. This feature allows Simplex coding to be optimal in terms of maximum pump peak power into the fiber before the onset of nonlinear effects. Note that other pulse coding schemes, such as Golay codes, are characterized by different number of pulses for different codewords, so that the maximum usable pump power is limited to a lower level (with respect to the use of Simplex codes) by the codeword containing the largest number of pulses ('1' bits).

Note that the implementation of a long-range Simplex-coded DPP-BOTDA sensor over SMF fibers turns out to be very challenging since the input power levels of the probe and coded-pump have to be properly adjusted to enhance the measurement SNR, avoiding at the same time pump depletion and nonlinear effects (such as modulation instability or self-phase modulation).

In addition, to avoid potential distortions due to acoustic-wave pre-excitation, Simplex coding must employ RZ-format pulses with an optimized duty cycle, allowing for a linear Brillouin amplification process which is independent of the coded bit distribution [10]. To further improve the sensing performance, optical pre-amplification at the receiver can also be employed [7]; nevertheless, its use in coded BOTDA sensors is not straightforward due to possible gain saturation, which can easily induce distortion in the coded traces. In our experiments, aiming at long sensing distances, the low input power at the receiver side allows for the use of an optical preamplifier operating in linear regime, avoiding then distortions of the coded-BOTDA traces.

3. Simulation results and sensor optimization

The effectiveness of the DPP-BOTDA technique strongly depends on the specific pulse-width pair used in the implementation [4]; in particular, pulse widths much longer than the acoustic-wave damping time (~10 ns) are required to avoid spectral broadening in the measured BGS [5]. However, to minimize the measurement time when using coding in DPP-BOTDA, the pulse width should be as short as possible to reduce the codeword period and to increase the efficiency of the coding technique.

In case of Simplex-coding based on non-return-to-zero (NRZ) pulses, the measured BGS can be distorted due to the Brillouin interaction among the pump pulses within the Simplex-code sequences and the acoustic wave generated by preceding pulses in the corresponding sequence [10]. In order to avoid this inter-pulse Brillouin interaction when using linear coding methods, such as Simplex codes, the use of RZ modulation format with an optimized duty cycle is essential.

In order to optimize the parameters of the Simplex coding technique (i.e. the pulse-width pair and the duty cycle of the RZ-format pulses) used in a DPP-BOTDA sensor, we have performed a set of simulations based on the following three-wave SBS transient model [8, 10]:

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$$\left(\frac{\partial}{\partial z}+\frac{1}{v_g}\frac{\partial}{\partial t}\right)E_P(z,t)=i\frac{1}{2}g_2(z)Q(z,t)E_S(z,t),$$
$$\left(-\frac{\partial}{\partial z}+\frac{1}{v_g}\frac{\partial}{\partial t}\right)E_S(z,t)=i\frac{1}{2}g_2(z)Q^*(z,t)E_P(z,t), \qquad (2)$$
$$\left(\frac{\partial}{\partial t}+\Gamma_A\right)Q(z,t)=ig_1(z)E_P(z,t)E_S^{\ *}(z,t),$$

where E_S, E_P and Q are the normalized slowly-varying amplitudes of the electromagnetic (optical pump and Stokes) and acoustic fields, $g_{1,2}$ are the electrostriction and electro-optic coupling coefficients respectively, $\Gamma_A = i(\Omega_B^{\ 2} - \Omega^2 - i\Omega\Gamma_B)/2\Omega$ is the local frequency detuning parameter, where $\Omega_B/2\pi$ and $\Omega/2\pi$ are the local Brillouin frequency shift (BFS) and the pump-probe frequency difference, respectively. The factor Γ_B is the acoustic damping constant, determining the Brillouin-gain spectral width $\Delta\nu_B = \Gamma_B/2\pi$ and the phonon lifetime $\tau_A = 1/\Gamma_B$.

The system of Eqs. (2) has been solved only for the resonance frequency $\Omega = \Omega_B$ using the analytical solution proposed in [8] exploiting a perturbation method. In this method, the general probe signal amplitude $E_S(z,t)$ is expressed as the sum of a constant factor $E_S^{\ 0}$ (equal to the probe signal at $z = 0$ when no Brillouin interaction takes place and the probe signal is only affected by the fiber attenuation) and a small varying component $e_S(z,t)$ which is proportional to the occurring Brillouin gain. In this way the total probe power P_S at the fiber input can be written as:

$$\begin{aligned}P_S\left(z=0,\Omega,t\right)&=\left|E_S^0+e_S\right|^2\\&\approx\left|E_S^0\right|^2+2\,\mathrm{Re}\left\{E_S^{0*}e_S\left(z=0,\Omega,t\right)\right\}.\end{aligned} \qquad (3)$$

The variations of the probe signal at the fiber input $e_S(z = 0,t)$ resulting from the local Brillouin amplification at a distance z_0 (at a time t_0) are obtained as a function of time t (for $t \geq t_0$ and $t_0 >> \tau_A$). The fiber-input signal power variation due to local small Brillouin gain (at resonance frequency Ω_B) can be then defined as [8]:

$$\Delta P_{IN,\Omega_B}\left(t\right)\equiv\mathrm{Re}\left\{E_S^{0*}e_S\left(z=0,\Omega_B,t\left|t\geq t_0,t_0>>\tau_A\right.\right)\right\}. \qquad (4)$$

It is worth noticing that the absolute probe signal variation depends on both pump and probe amplitudes at a given interaction point z_0; thus, in order to assess the Brillouin gain at fiber location z independently on the optical power levels, the gain has been obtained by normalizing the probe signal power variations ΔP by the probe and pump power traces [8]. Moreover, in BOTDA sensors the strain-temperature information is obtained by the (spectral) gain variations rather than the absolute gain along the sensing fiber. Therefore, after obtaining the Brillouin gain by the system of Eqs. (2) and Eq. (4), the maximum gain level is normalized to 1 (corresponding to the SBS gain occurring when the acoustic field is fully activated). This allows us to evaluate the transients of the acoustic wave and their impact on the differential Brillouin gain when Simplex coding is applied to DPP-BOTDA sensors.

In our DPP-BOTDA experiment aiming at a 20 cm spatial resolution, the differential Brillouin gain has been calculated by subtracting the Stokes signals resulting from a pair of two different pulsed schemes with a pulsewidth difference of 2 ns. This condition, in a coded scheme, must be optimized as a function of the single pulse width, in order to maximize acoustic-wave excitation and gain. Figure 1 actually shows the normalized differential Brillouin gain for the Stokes signal (at the maximum gain frequency) versus the width of the used pulse pair (the *x*-axis in this figure represents the longest pulse-width of the respective pair). From the figure it can be observed that, if pulse-width pairs shorter than 58/60 ns are used, the differential Brillouin gain does not reach its maximum level due to the relatively short acoustic-wave excitation. However, if the pulse-width pair is longer than 58/60 ns, the acoustic field is fully activated, resulting in an optimized Brillouin amplification process.

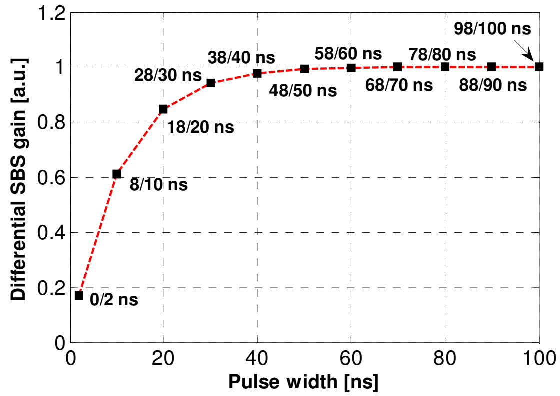

Fig. 1. Normalized differential Brillouin gain as a function of the pair pulse-width, for a pulse-width difference of 2 ns (the *x*-axis represents the longest width of the pair).

Figure 2 shows a typical differential SBS gain time waveform (resulting from DPP-BOTDA) when 58/60 ns pulse-width pair is used with coded NRZ pulses (for clarity, the corresponding pump-pulse amplitude waveforms are also shown). We can observe that, for the first bit (time) slot of the coding, the subtraction process allows for a 2-ns differential Brillouin amplification, as expected from the single-pulse DPP-BOTDA technique. However, it is worth noticing that the bit slots within the codeword following the first one can be affected by distortion due to the nonlinear Brillouin amplification resulting from the pre-activated acoustic field, which depends on the specific bit pattern in each codeword. It is evident in Fig. 2 that even small differences in each Brillouin interaction time (i.e. 58 ns and 60 ns) lead to different amplification levels in successive bit slots (due to the residual SBS gain resulting from previous bits in the pulse sequence), inducing a slightly different amplification in next bits of the Simplex-codes sequence. Thus, when Simplex coding is used with NRZ pulses, the resulting nonlinear Brillouin amplification levels strongly depend on the bit distribution within each codeword (bit patterning effect on SBS gain), leading to distorted BOTDA traces after decoding.

As shown in Fig. 2, such a pattern-dependent SBS interaction generates a residual Brillouin gain (up to about 18% with respect to the maximum differential gain) after subtraction in differential pulse-width pairs with coded traces, leading to potential distortions in the measured BGS [10] and degradation of the spatial resolution. Considering that the Simplex-decoding process [5] requires a linear Brillouin amplification [10], the interaction among the acoustic wave and every pulse in a Simplex-coded sequence has to be properly designed in order to suppress any residual differential gain (and the consequent impact on the spatial resolution and measured BGS) when using DPP-BOTDA sensors.

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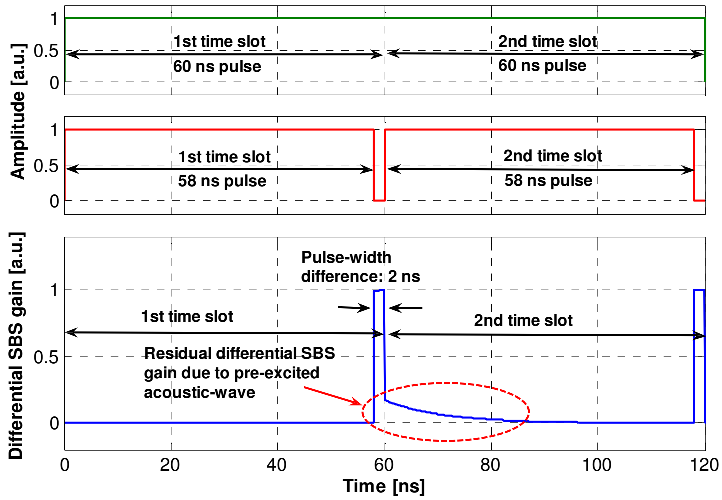

Fig. 2. Normalized differential SBS gain as a function of time, resulting from the differential pulse-width pair technique when using a 58/60-ns pump pulse pair (the normalized pulse amplitude is also shown). For clarity only the interaction of the first 2 bits of a Simplex-coded sequence is reported.

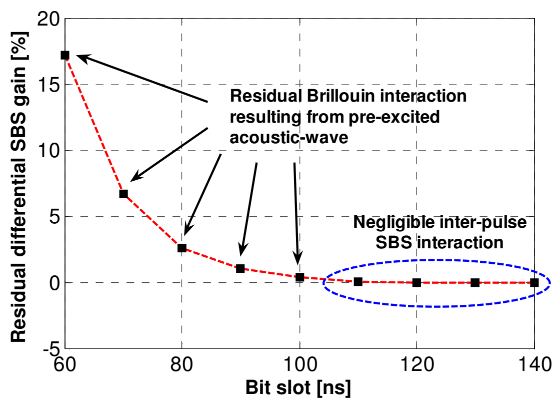

Fig. 3. Additional Brillouin gain (as a function of the time slot) resulting from nonlinear inter-pulse Brillouin interaction when using Simplex-coding in DPP-BOTDA sensors.

In order to avoid inter-pulse Brillouin interaction when using Simplex coding in DPP-BOTDA sensors, pulses with RZ modulation format [10] have to be employed. Figure 3 illustrates the impact of the bit time slot on the maximum level of the residual Brillouin gain resulting from the nonlinear interaction between Simplex-coded pulses and the pre-excited acoustic wave (in this figure, 100% represents the differential Brillouin gain occurring with a fully excited acoustic wave). We can observe that when subtracting BOTDA traces with 58/60 ns pulse pair using NRZ pulses (slot time: 60 ns), the different levels of activation of the acoustic field induce a residual Brillouin gain of about 18% (as also evident in Fig. 2). This nonlinear Brillouin amplification is reduced when the bit time slot is increased (i.e. using smaller duty cycles); in particular, the inter-pulse SBS interaction can be neglected for bit slot values longer or equal than 110 ns (for 58/60 ns pulse widths). As a result of the optimization process, in the following experimental Simplex-coded DPP-BOTDA sensor a 58/60-ns pulse-width pair will be used with a RZ format and 120-ns (50% duty cycle) bit slot.

4. Experimental setup and results

Figure 4 shows the experimental setup implementing a Simplex-coded DPP-BOTDA sensor. A 3-dB optical coupler has been used to split the CW light from a distributed-feedback (DFB) laser (1550 nm, P_{IN} = 10 dBm) into the (CW) probe and (pulsed) pump branches.

The Simplex-coded pulsed pump signal is generated by using a high extinction-ratio Mach-Zehnder modulator (MZM) controlled by a waveform generator encoding the required Simplex pulse sequences. In particular, Simplex codewords with 511 bit and RZ modulation format have been used in this case. Optical amplification of the pump light through an Erbium-doped fiber amplifier (EDFA) and a polarization controller (PC) are employed before the MZM to avoid codeword distortions. Actually, the Erbium-lifetime scale of the EDFA is expected to induce gain-dynamics-related distortions in the coded pulse sequences, and therefore, the EDFA has to be necessary placed before pulse generation in the pump branch. Resulting coded pulses exhibit 16 dBm peak power at the fiber input, 120 ns bit slot and a pulse-width pair of 60/58 ns (fall time < 1 ns), thus allowing for a spatial resolution which is expected to slightly exceed 20 cm, due to the detrimental effects of the limited pulse fall time, as detailed below [11].

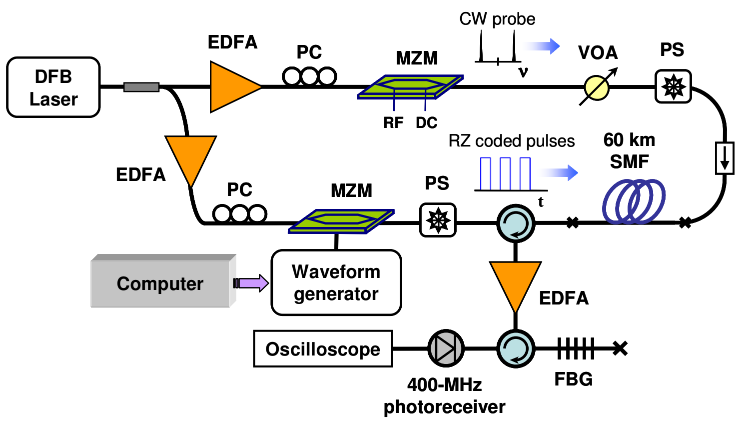

Fig. 4. Setup of implemented Simplex-coded DPP-BOTDA sensor.

The probe signal with suitable frequency shift from the pump wave is generated through the double-sideband technique [9] employing RF-modulation of the laser light using an MZM driven by a microwave generator. The carrier frequency has been suppressed by a proper DC bias setting in the MZM, and the probe frequency is then tuned around the Brillouin frequency shift value for distributed spectral measurements of the Brillouin gain along the sensing fiber. An EDFA has been used to compensate for the insertion loss of the optical components, and a variable optical attenuator (VOA) is used to suitably adjust the probe power that is launched into the fiber (P_{IN} = −11 dBm), avoiding pump depletion and nonlocal effects. Two polarization scramblers (PS), one for each branch, are used to reduce gain oscillations in the polarization-dependent Brillouin amplification process. Simplex-coded pump and CW probe lights are launched in counter-propagating directions along 60 km of standard SMF. Note that the propagation of both spectral sidebands of the probe signal reduces pump depletion and nonlocal effects [9], thus counteracting the main factors limiting sensing distance in long-range BOTDA sensors.

At the receiver-stage, an EDFA operating in linear gain regime (~22 dB net small signal gain) is used to amplify the coded-probe signal. The Stokes signal is extracted through two optical circulators and a fiber Bragg grating (FBG) with 6-GHz bandwidth (~6.1 dB total insertion loss for the Stokes probe signal through the optical component cascade after the pre-amplifier), and then detected by a 400-MHz photo-receiver, which is connected to a computer-controlled oscilloscope to carry out the acquisitions.

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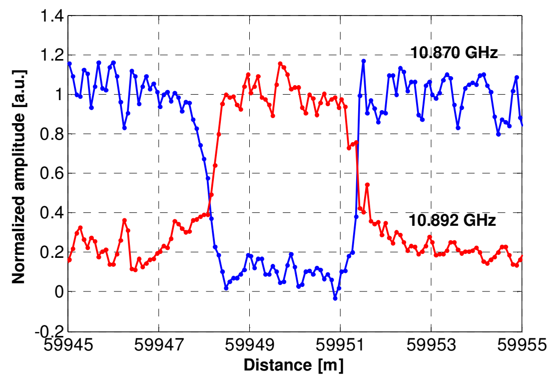

Fig. 5. Decoded differential BOTDA trace versus fiber length in proximity of fiber end, for two probe signal frequency shift values (10.870 GHz and 10.892 GHz), showing Brillouin gain variations for the fiber lying inside the TCC.

To verify the performance of the implemented Simplex-coded DPP-BOTDA sensor, 3 meters of fiber near the far fiber-end have been placed inside a temperature-controlled chamber (TCC), whose temperature has been set to 45°C, while the rest of the fiber is kept at room temperature (23°C). DPP-BOTDA coded traces with 60 ns and 58 ns pulse-widths (30 time-averaged acquisitions per coded trace) are decoded and then subtracted to obtain the BGS as a function of the distance. Figure 5 shows the decoded differential BOTDA trace versus fiber length in proximity of the fiber end, resulting from measurements at two different probe signal frequency shift values (10.870 GHz and 10.892 GHz). In Fig. 5 the variation of Brillouin gain for both probe frequency values due to the increased temperature is evident in the fiber spool lying inside the TCC (approximately between 59948 m and 59951 m).

By tuning the probe signal over a frequency span around the BFS (with respect to the Brillouin pump), the exact shape of the Brillouin gain spectrum has been measured throughout the fiber length. Figure 6 shows the obtained BGS near the far fiber-end, where we can clearly observe the induced BGS shift corresponding to the heated fiber spool.

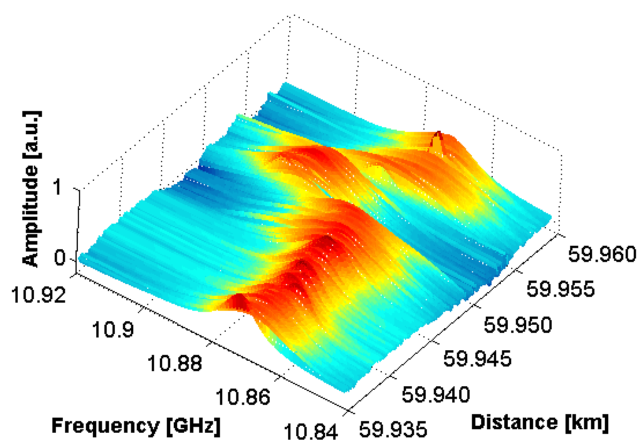

Fig. 6. Measured (decoded) BGS as a function of the distance near the far fiber-end (~60 km).

While the BFS at room temperature was measured to be 10.87 GHz near the fiber end, its value increased of ~22 MHz (up to ~10.892 GHz) inside the TCC at higher temperature (45°C), in agreement with the temperature sensitivity (about 1 MHz/°C) of the used SMF fiber.

Note that the combined use of optical pre-amplification and Simplex coding is particularly effective to enhance the sensing performance, allowing for probe signal measurements with a

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significantly enhanced SNR. In particular, the SNR enhancement obtained due to the use of optical pulse coding was measured to be ~10.3 dB with respect to a standard trace acquisition (without coding) and considering the same number of time-averaged traces (i.e. similar measurement time). This enhancement is in good agreement with the theoretical expectation of ~10.54 dB coding gain found for Simplex codes with 511 bit [5]. On the other hand, it is worth mentioning that the use of pre-amplification is not straightforward in coded-BOTDA systems since it might easily induce distortions of the coded traces due to amplifier gain saturation. In our case no distortion was observed because of the long used sensing range and the consequent small power levels in the received trace, pointing out the effectiveness of using linear-operating EDFA in long-range sensing. The impact of pre-amplification is significant in long-distance BOTDA, since the SNR of the probe signal from far fiber end with no pre-amplification is essentially limited by electrical noise, due to the low light power levels at the receiver. Figure 7 shows the decoded BOTDA traces at the peak Brillouin gain (when using 60 ns pulse) with and without pre-amplification. The impact of pre-amplification is evident near the far fiber end, where we can clearly quantify the obtained SNR enhancement. In particular, the use of pre-amplification allowed us to extend the dynamic range of DPP-BOTDA acquisitions, attaining an SNR enhancement of ~9 dB for the probe signal at far fiber-end. This value is significantly smaller than the above-mentioned amplifier gain (22 dB), since, as also pointed out in [7], the SNR benefits arising from the pre-amplification are reduced due to the added amplified spontaneous emission (ASE) noise introduced by the EDFA. This issue leads to an SNR which is limited by optical noise, and therefore, a reduced SNR improvement is obtained in the BOTDA traces.

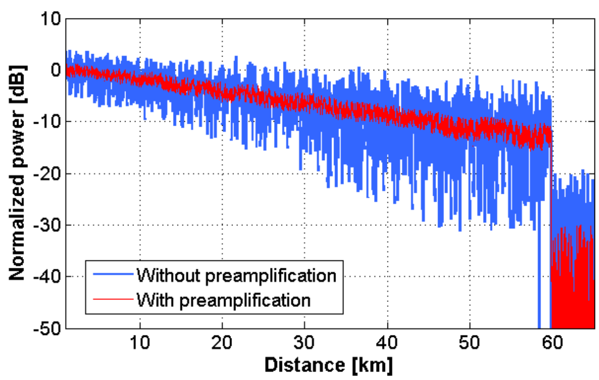

Fig. 7. Decoded BOTDA traces at the Brillouin gain peak when using 60 ns RZ pulses and 511-bit Simplex coding, with (red line) and without (blue line) optical pre-amplification.

By fitting the measured BGS with a Lorentzian curve and calculating the BFS, the temperature profile along the fiber has been obtained. The corresponding noise $\delta\nu_B$ (or equivalently SNR and resolution) in the fitted Brillouin frequency shift can then be inferred from the Brillouin gain SNR and BGS linewidth ($\Delta\nu_B$) through the following relation [10]:

$$\delta\nu_B = \frac{\Delta\nu_B}{\sqrt{2}\left(SNR\right)^{1/4}}. \quad (5)$$

The achieved spatial resolution near 60 km distance has been estimated from the 10%-90% response to the temperature step near the TCC (assumed as step-like thanks to the insulating properties of the used fiber cable), and was found to be ~25 cm, as indicated in Fig. 8. The discrepancy between the theoretical and experimental resolution values can be explained considering the non-ideal fall time of the pulses, linked to the limited bandwidth of opto-electronic components, such as the used waveform generator. As recently shown in [11] for DPP-BOTDA systems, non-negligible pulse fall-times can have a significant impact in the attained spatial resolution. In our case the pulse fall time (< 1ns, as mentioned above), is a negligible fraction of the original pulse-width (58 ns or 60 ns), but is a non-negligible fraction of the differential pulse-width value (2 ns), and is then expected to worsen the spatial resolution as reported in [11]. Note that the use of optimized Simplex-coded pulses in RZ modulation format with 50% duty cycle avoids acoustic-wave pre-excitation and the related penalties, i.e. BGS distortions and strong oscillations near abrupt BFS variations, thus allowing for distortion-free BGS measurements.

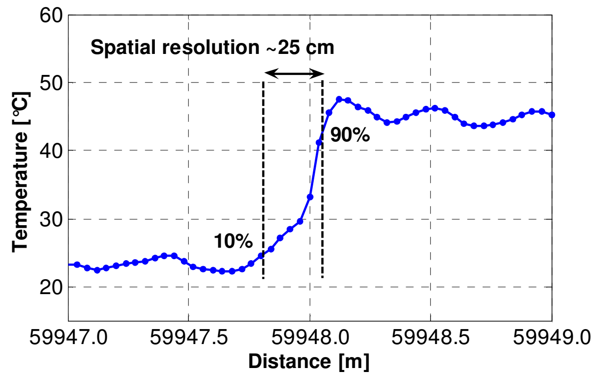

Fig. 8. Temperature profile as a function of the distance near the far fiber-end (~60 km).

The achieved temperature resolution has been calculated through the standard deviation of the BFS trace, resulting in 1.2 MHz near 60 km distance, which corresponds to a temperature resolution of ~1.2°C (or equivalently to a strain resolution of 24 με).

5. Conclusions

In conclusion, we performed a theoretical analysis and experimental implementation for optimized Simplex-coded DPP-BOTDA sensing with RZ modulation format. A parameter optimization for coded-pulse technique applied to DPP-BOTDA sensing was carried out by solving a three-wave SBS transient model. In particular, we employed an optimized duty-cycle RZ modulation format for 511-bit Simplex coding and optical pre-amplification at the receiver, allowing for the first demonstration of a Brillouin sensor with 25 cm spatial-resolution over 60 km standard single-mode fiber, this being equivalent to more than 240k discrete sensing points, with a temperature (strain) resolution of 1.2°C (24 με) over the fiber length.

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